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On the soft X-ray spectrum of cooling flows

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ABSTRACT
Strong evidence for cooling flows has been found in low resolution X-ray imaging and spectra of many clusters of galaxies. However high resolution X-ray spectra of several clusters from the Reflection Grating Spectrometer (RGS) on XMM-Newton now show a soft X-ray spectrum inconsistent with a simple cooling flow. The main problem is a lack of the emission lines expected from gas cooling below 1–2 keV. Lines from gas at about 2–3 keV are observed, even in a high temperature cluster such as A 1835, indicating that gas is cooling down to about 2–3 keV, but is not found at lower temperatures. Here we discuss several solutions to the problem; heating, mixing, differential absorption and inhomogeneous metallicity. Continuous or sporadic heating creates further problems, including the targetting of the heat at the cooler gas and also the high total energy required. So far there is no clear observational evidence for widespread heating, or shocks, in cluster cores, except in radio lobes which occupy only part of the volume. The implied ages of cooling flows are short, at about 1 Gyr. Mixing. or absorption, of the cooling gas are other possibilities. Alternatively, if the metals in the intracluster medium are not uniformly spread but are clumped, then little line emission is expected from the gas cooling below 1 keV. The low metallicity part cools without line emission whereas the strengths of the soft X-ray lines from the metal-rich gas depend on the mass fraction of that gas and not on the abundance, since soft X-ray line emission dominates the cooling function below 2 keV.

Key words: galaxies: clusters: – cooling flows – X-rays: galaxies

1 INTRODUCTION

X-ray spectra of the cores of clusters with cooling flows made with the Reflection Grating Spectrometer (RGS; den Herder et al 2000) on XMM-Newton show a remarkable lack of emission lines from gas at 1 keV or below. For the cluster A 1835, at redshift $z = 0.2523$, both Chandra (Schmidt et al 2000) and XMM-Newton (Peterson et al 2000) CCD spectra show a strong temperature decrease towards the cluster centre from about 9 keV down to about 3 keV. RGS spectra (Peterson et al 2000) are well fitted by a model of gas cooling over that energy range, at a rate of about $1000\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$, but not to lower temperatures. There is clear evidence for emission lines from FeXXIV, but not from lower ionization stages such as FeXX–XXII and in particular FeXVII which characterize gas cooling through temperatures of 1 keV and below, respectively. The limit on the rate of gas cooling below 1 keV is about $150\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$. A similar temperature decrease inward is seen in Chandra (Fabian et al 2000b) and XMM-Newton (Tamura et al 2000) CCD spectra of A 1795 ($z = 0.063$), again with no emission lines from gas cooling through and below 1 keV apparent in the RGS spectra (Tamura et al 2000). The low temperature cooling rate limit in this case is about $140\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$, which is close to the total cooling rate inferred from ASCA spectra (Fabian et al 1994; Allen et al 1999).

Various explanations for this disagreement with simple cooling flow expectations (see Fabian 1994 for a review) are given by Peterson et al (2000). Just invoking a heat source is not sufficient, unless it has very specific properties, since gas does not appear to accumulate at 3 keV, it appears to cool down to that temperature then vanish. Moreover, since gas at 3 keV occupies less than 6 per cent of the volume of gas at 9 keV, any heating needs to be targetted. It is possible that the 3 keV gas mixes with hotter or much colder gas, or absorption becomes important for cooler gas. We discuss these problems and possibilities here in more detail.

Finally we advance a new possibility involving strong metallicity variations in the intracluster gas. The line radiation from intracluster gas above 3 keV is proportional to its metallicity, but if it cools to lower temperatures where line radiation dominates the cooling function, the predicted line strengths depend on the mass fraction of the gas which is metal rich. That fraction may be small.

2 HEATING

Many authors have suggested that radiative cooling in cluster cores is offset by some form of heating. Some scenarios invoke conduction with the hot gas being the heat source (Tucker & Rosner 1983; Bertschinger & Meiksin 1986; Gaetz 1989). Others suggest that activity from the nucleus of the central galaxy is responsible (Rosner & Tucker 1989; Böhringer & Morfill 1989; Loewenstein, Zweibel & Begelman 1991; David & Tucker 1997; Binney & Tabor 1995; Soker et al 2000; David et al 2000).

We note that the mass of gas at about 3 keV in A 1835 is consistent with that expected from radiative cooling of the hotter 9 keV gas. The radiative cooling time, t_c, of gas at 3 keV is about 20 per cent of that at 9 keV (for bremsstrahlung cooling at constant pressure $t_c \propto T^{3/2}$; $t_c(3\,\mathrm{keV}) \sim 1$ Gyr or less in A 1835), so in a steady flow the mass of gas below 3 keV is only 20 per cent of that below 9 keV, within the flow. If gas were accumulating at 3 keV for the lifetime of the flow, then there would be 5 times more of it than expected from steady cooling alone. This is inconsistent with the observed mass fractions. If steady heating is responsible then it has to be some form of 'complete' heating which takes the gas back up to the hotter temperature, since there is no evidence for significant amounts of gas at other temperatures.

One mechanism for this has been suggested by Norman & Meiksin (1996). They propose that the magnetic topology of the gas changes as it cools down and at some point, say 3 keV, reconnection enables rapid thermal conduction to occur between the cooler gas and the hotter surrounding gas. Why this should happen throughout the flow at 3 keV is unclear. It could be that magnetic fields pin cooling blobs into comoving with the flow until the density contrast becomes so great that they fall and mix into the surrounding hotter gas, or perhaps this is when magnetic fields dominate the pressure (for a cooling spherical cloud, magnetic pressure $P_B \propto T^{-4/3}$). As noted by Norman & Meiksin (1996), mechanisms such as this do not actually stop the cooling flow altogether since energy is being lost, unless the hotter phase is thermally coupled by conduction to the outer hot gas beyond the cooling flow. Chandra images of 'cold fronts' in some clusters (Markevitch et al 2000; Vikhlinin et al 2000) indicate that conduction there is highly suppressed (Ettori & Fabian 2000).

Note too that the volume occupied by gas below temperature T in a cooling flow $\propto T^{5/2}$ if bremsstrahlung dominates; below a few keV where line cooling dominates then the dependence is steeper. This means that gas below 3 keV in a flow originating at 9 keV occupies less than 6 per cent of the volume of the hotter gas. Heating must be targetted at this small volume if cooling down to 3 keV is to take place. The volume is yet smaller if we allow for gravitational work done on the gas.

Thermal conduction also has a steep temperature ($T^{5/2}$ if proportional to the Spitzer rate) which means that it will operate principally in the hotter gas rather than in the cooler gas in the system (see also discussion by Bregman & David 1988).

An alternative to steady heating is sporadic heating, The nucleus, for example, may have short intervals of strong activity interspersed with periods of relative quiescence. Several heating models have been proposed along these lines (Rosner & Tucker 1989; Tucker & David 1997; Binney & Tabor 1995, Soker et al 2000). In an analysis of Chandra data of the Hydra A cluster, David et al (2000) find from spectra that the rate at which gas cools to low temperatures in the inner 30 kpc is inconsistent with the rate of gas flow into this region and invoke sporadic heating by the radio source to heat the remainder.

Problems with this scenario are a) the large energy input required and b) efficient coupling of that energy to the gas. For example, the thermal energy of the gas within 100 kpc of the centre of A 1835 is about $3 \times 10^{61}\,\mathrm{erg}$. To heat two-thirds of this (i.e. to take the gas back from $3\,\mathrm{keV} \rightarrow 9\,\mathrm{keV}$) requires a power of $2 \times 10^{46}\,\mathrm{erg\,s^{-1}}$ for $3 \times 10^7\,\mathrm{yr}$ if the coupling efficiency is 100 per cent. This exceeds the total power of an extreme (and rare) radio source such as 3C295 (Allen et al 2000, where the radio emission in assumed to be only 10 per cent of the radio power). Most of the power of such sources is however deposited beyond the core since the lobes propagate through the intracluster medium rapidly ($\sim 10^7\,\mathrm{yr}$ to cross 100 kpc for 3C295, using the radio hot spot speed of Perley & Taylor 1991).

Lower powers could be used for longer times, but then the probability of seeing a cooling flow being heated becomes significant and no such example has yet been identified. Observations of cooling flows around radio sources, e.g. 3C295 (Allen et al 2000) and 3C84 (Fabian et al 2000a), show no evidence for heating taking place beyond the radio lobes, which occupy only a small fraction of the volume. Indeed in the case of 3C84 in the Perseus cluster the data show that the *coolest* gas in the core lies immediately around the radio lobes (Fabian et al 2000a; see also Böhringer et al 1995 for M87, where the gas close to the radio lobes is cooler than the surrounding gas). Nevertheless, heating of some of the gas (at least that in the lobes) in cluster cores by radio sources must take place. Whether it can be sufficient to offset cooling in a massive system such as A 1835 is unknown. A major problem is that no cluster yet shows the heating taking place in a widespread manner; no strong shocks, which Soker et al (2000) invoke as the main distributed heat source set up by radio jets, have been found in cluster cores. If heating is the solution then jets may be considerably more powerful than their radio luminosity implies.

If a cluster is heated from near to its centre, the details of the heating process do not have a major effect on the structure of the heated gas. The principal issue is the rate of heating relative to the size of the region that is heated appreciably. In a heating event where the heating rate exceeds the thermal energy of the gas divided by its sound crossing time, a shock forms and the heated gas will usually be left in a convectively unstable state. The hottest gas may then rise well outside the heated core as the atmosphere returns to convective equilibrium in a few free-fall times. Lower heating rates do not produce a shock, although they still tend to make the heated gas convectively unstable. However, for low heating rates convective motion has time to maintain near convective equilibrium while the gas is being heated, so that the whole of the region that is heated significantly becomes nearly isentropic. This means that in order for slow heating to prevent deposition of cold gas from a cooling flow, the whole of the region that would otherwise be the cooling flow becomes isentropic. This is not consistent with the data if the temperature declines towards the centres of these clusters is due to radiative cooling. Fast heating would also result in a nearly isentropic core between heating events, but need not make the whole of the region where there is net heating isentropic (David et al. 2000). Observed abundance gradients (Ezawa et al 1997) are also inconsistent with a convective core.

We have previously argued that wind power from accreting black holes may have been responsible for heating the intracluster medium in all clusters, in order to explain the observed luminosity–temperature relation (Wu, Fabian & Nulsen 2000). We envisage this process happening at earlier times (redshifts greater than one) than the heating in the present discussion, and also to originate from most of the cluster galaxies. Heating by the nucleus of the central cluster galaxy could be seen as the remnant of a continuum of heating activity by galactic nuclei, provided the problems discussed above can be overcome.

A merger with another cluster may also disrupt a cooling flow (see discussion in Allen et al 1999 and Gomez et al 2000). For the mean age of cooling flows to be about 1 Gyr or less, as is required from the typical cooling time of gas at 2–3 keV at the pressure near the centre of a cluster, the merger rate must be high. Small clusters or groups are the only plausible merger partners (no evolution is seen in the cluster luminosity function within $z = 0.3$; Ebeling et al 1997). Again, how such a process could apparently target the coolest X-ray emitting gas in a cluster core is unclear.

3 MIXING

If cooling does take some gas down to say 10^4 K then mixing of hotter gas with that cold gas could cause it to be undetectable in the X-ray band. In the case of A 1835 there are considerable amounts of gas at $10^3 - 10^4$ K within a radius of $20\,\mathrm{kpc}$ from the centre seen in optical line emission (Allen 1995; Crawford et al 1999), and over $10^{11}\,\mathrm{M}_\odot$ of molecular gas have been reported (Edge et al 2000).

The mixing process could resemble a mixing layer as discussed by Begelman & Fabian (1990). Momentum constrains the relative quantities of gas at high T_h and low T_l temperatures which mix such that the final temperature is approximately $\sqrt{(}T_\mathrm{h}T_\mathrm{l})$. This means that gas at 3×10^7 K mixing with gas at 3×10^3 K ends at a temperature of $\sim 3 \times 10^5$ K. Such gas will cool very rapidly and add to the gas mass at the lower temperature.

Gas cooling within a blob is likely to be thermally unstable, with the denser cooler gas falling, shredding and mixing into the surrounding less dense parts. This too could lead to much of the thermal energy of a blob being radiated in the EUV, rather than in soft X-rays.

The relevance of cool mixing may be testable by UV observations of the strong line emission expected from gas at $10^5 - 10^6$ K and optical observations of coronal line emission. Mixed gas in A 1795 would have to be below $10^{5.5}$ K in order to be consistent with the results of Yan & Cohen (1995). Reprocessing of UV emission by colder gas could explain some of the optical emission lines from the central regions of cooling flows (Heckman et al 1989; Crawford et al 2000; Donahue et al 2000). The total power radiated in these lines (which is about 20 times that detected in Hα, for which the luminosity $L(\mathrm{H}\alpha)$ ranges from $10^{41} - 10^{43}\,\mathrm{erg\,s^{-1}}$) is similar to that associated with the gas cooling from about 1 keV. There is not therefore any problem here with the energetics, indeed there is a good correspondence with the missing energy from gas cooling below 1 keV and the total power radiated by the optical nebulosity, although ionization by massive young stars presumably accounts for some of $L(\mathrm{H}\alpha)$.

4 DIFFERENTIAL ABSORPTION

The deficit of emission below 1 keV seen with ROSAT (Allen & Fabian 1997) and ASCA (Fabian et al 1994; Allen et al 1999) has often been ascribed to absorption internal to the cooling flow. The models used have however generally been very simple screens across the whole flow. If instead the absorption only operated on the cooler gas, say that below 3 keV which, as noted above, occupies only a few per cent of the volume, then the X-ray emission lines from cooler gas could be rendered undetectable. The required column densities would be in the range of a few 10^{21} to $10^{22}\,\mathrm{cm}^{-2}$.

If the flow was not highly multiphase, then much of the cooler gas would be near the centre which is also where most of the absorbing gas would need to lie. This gas could either be in sheets and filaments of cooled gas, or cooled parts of cooling clouds. The implied mass of absorbing gas is similar to that assumed to be deposited by the cooling flow over a few Gyr (Allen et al 1999). Again, the optical nebulosity commonly seen in this region may also be involved. Observation of patches of absorption, in both soft X-ray lines and continuum would test this possibility.

Resonance scattering may also be important for soft X-ray resonance lines. The 15.01 A emission of FeXVII, which is produced by gas at around 4×10^6 K is a key line missing from the observed spectra. This line is weakened in Solar spectra by resonance scattering (see e.g. Rugge & McKenzie 1985). Using the formula presented by Rugge & McKenzie (1985), we find that the optical depth for that line in a large flow such as in A 1835 could exceed 100. (The mass of gas around 4×10^6 K is obtained from the product of the cooling time at that temperature, $t_\mathrm{c} \sim 3 \times 10^6\,\mathrm{yr}$, and the mass cooling rate, $\sim 1000\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$; the column density is then obtained using the pressure, $\sim 2 \times 10^6\,\mathrm{cm}^{-3}$ K .) Such a high optical depth can increase the total path length of the resonant line photons by a factor of a 2–3, making them more prone to absorption by cold gas. Also, if there is a widespread distribution of cooling gas, then some line emission can be scattered beyond the 1 arcmin effective field of view of the RGS.

5 METALLICITY VARIATIONS

Consider that the intracluster medium is highly inhomogeneous, not principally in density or temperature but in Z, the metallicity. Although there is little evidence for this, it is not obvious that the metals ejected from galaxies and supernovae should mix into a magnetized hot gas very easily. The strong continuous shear in the disc of a spiral galaxy may mix gas fairly well there, but the situation is far different in the intracluster medium. We assume that the scale of the metal-rich clumps is very small ($\ll 1\,\mathrm{kpc}$) so is spatially unresolved.

Let 90 per cent of the gas have zero metallicity ($Z = 0$) and 10 per cent have 3 times Solar ($Z = 3$), i.e. the metallicity is bimodal. The spectrum of such gas then looks on average just like one with $Z = 0.3$. The iron ions, for example, radiate in the same way wherever they are located in the optically-thin intracluster medium.

What happens now as the gas cools. i.e. in the central cooling flow? If the gas starts at $kT = 10\,\mathrm{keV}$ bremsstrahlung cooling dominates in all the gas. Line cooling only dominates the cooling function below about 2 keV for gas around Solar metallicity (see Böhringer & Hensler 1989; the temperatureat which it happens increases with metallcity). The metal-rich gas cools together with the metal-poor gas until about 2 keV below which it cools much faster and drops out. The line emission from the cooling flow is only from the metal-rich gas which is only one tenth of the total flow.

The line strengths are not 10 times what they would have been for that gas had it had Z=0.3, since the gas only has so much thermal energy, most of which comes out from the lines. The line intensity depends on $\dot{M}$ rather than Z where line cooling dominates (it does depend on Z at higher temperatures). The net effect is that the cooling lines from the whole flow are much weaker than they would be were the gas fully mixed. In summary, when the gas is not cooling

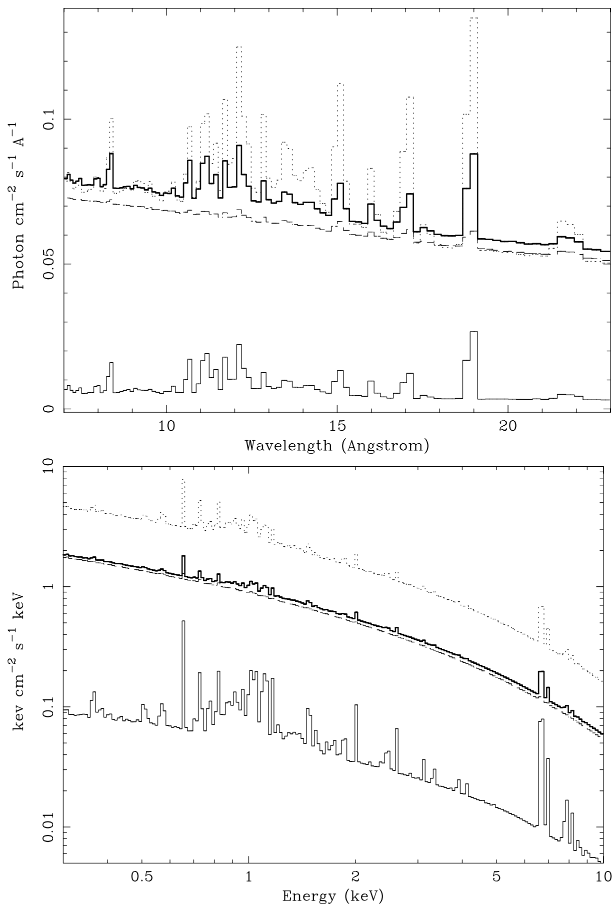

Figure 1. Comparison of cooling flow spectra from gas with differing metallicities. All have an upper temperature of 9 keV. Upper panel: the bottom spectrum is $10\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$ of gas with $Z = 2$, then successively above are $100\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$ at $Z = 0.01$, the sum of these two (bold solid line), and finally $110\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$ at $Z = 0.2$ (dotted line). Much of the line emission from 11 – 17 A is iron L shell emission (XXIV to XVII roughly going from left to right in the figure, FeXVII accounts for the emission at 15 and 17 A); OVIII emission is at 19 A. Lower panel: similar to the upper panel but plotted against energy and with a range showing the iron K lines; the top curve (dotted line) is for a $Z = 0.2$ flow with a higher rate of $330\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$ so there is no overlap. The spectra of non-cooling hot gases corresponding to the top two models (a $10 : 1$ mixture of gas at $Z = 0.01$ and $Z = 2$, and gas at $Z = 0.2$) would be indistinguishable.

it looks like gas with $Z = 0.3$. But when it is radiatively cooling, particularly below 2 keV, it looks like much lower metallicity gas.

The X-ray emission from such a inhomogeneous-metallicity flow resembles the sum of a metal-poor one and a metal-rich one. This is illustrated in Fig. 1. If the gas is simply of two varieties, one with metallicity 0 and the other with mass fraction f and metallicity Z, then the cooling flow will approximate a standard (mixed) one of mass cooling rate $\dot{M}$ down to where the lines dominate cooling in the metal-rich gas, with metallicity fZ (the lower panel in Fig. 1 shows that the iron K lines are close in relative strength to those from the mixed gas). Below that temperature the soft X-ray lines will be appropriate for a flow of only $f\dot{M} = Z_{\rm obs}\dot{M}/Z$, where $Z_{\rm obs}$ is the observed (average) metallicity (Fig. 1 shows that the iron L lines are much weaker than those from the mixed gas).

Note that if the oxygen abundance is high in a flow (or there were regions with enhanced oxygen abundance which cool separately) and they became an important coolant in the X-ray range then the oxygen line fluxes depend on the cooling rate, not the abundance too. Determinations of abundance from cooling flows are inherently complicated, more so if the metallicities of different elements are inhomogeneous. This is also relevant to the hot gas commonly seen in elliptical galaxies.

If the metal-rich gas begins cooling at a larger radius than the metal-poor gas (the line emission will help to do this, but the metal-rich gas could also be slightly denser too) then the X-ray emission spectrum will be complicated to analyse. It is possible that some of the abundance gradients seen in the cores of some cooling flow clusters (e.g. Ezawa et al 1997) could be due to these effects.

A possible way to test the inhomogeneous metallicity solution is to search for metallicity variations in the intracluster medium using high spatial resolution images (Chandra and XMM-Newton). Also, if the optical line-emitting nebulosity at the centres of cooling flows is due to the metal-rich gas then abundance determinations of that gas may provide a clue.

6 DISCUSSION

We have shown that the XMM-Newton RGS soft X-ray spectra of cooling flows are difficult to interpret. There are problems with many solutions. Sporadic heating, mixing, differential absorption and inhomogeneous metallicity offer possible solutions. If the last proves correct then it has wide implications for the enrichment of both the intracluster medium, and the intergalactic medium which presumably would also have a patchy metallicity. Some issues to do with whether the metals from the first stars are mixed uniformaly into the intergalactic medium or not are discussed by Rees (1997). The chemical evolution of galaxies might also become complex, with bimodal populations*.

One possible advantage with a heating explanation is that there is no, or little, mass deposition. This means that the problem of the fate of the cooled gas in a standard cooling flow is avoided. As already mentioned however there is strong evidence for massive star formation and cooled gas in many cooling flows.

If hot mixing or heating solutions apply to cooling flows then they may well apply to the formation of all galaxies by cooling. There has long been an assumption that the visible matter in galaxies is that which could cool on an infall time (Rees & Ostriker 1977; White & Rees 1978). Massive galaxies do however accrete large hot envelopes of gas where the cooling time exceeds the infall time but is still less than the age of the Universe; i.e. they have cooling flows (Nulsen & Fabian 1995). Whether such gas cools and builds galaxies further or is heated and prevented from cooling is not known. Heating by a central engine is one solution. The consequence of this is that the central engine (the growth of the central black hole) then has a profound influence on the final state of the galaxy.

Further observations of the soft X-ray phenomenon in cooling flows therefore have potential implications for our understanding of cooling and heating generally, as well as for the uniformity of metal enrichment of hot gas, the energy content of jets, and galaxy formation.

* The globular cluster population of M87 has a bimodal colour distribution which has been intrepreted as due to the later merger of a metal-rich galaxy (Kundu et al 1999). Formation from gas with bimodal metallicity is an alternative possibility.

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